



# **High Brightness Electrodeless Z-Pinch™ EUV Source for Mask Inspection Tools**

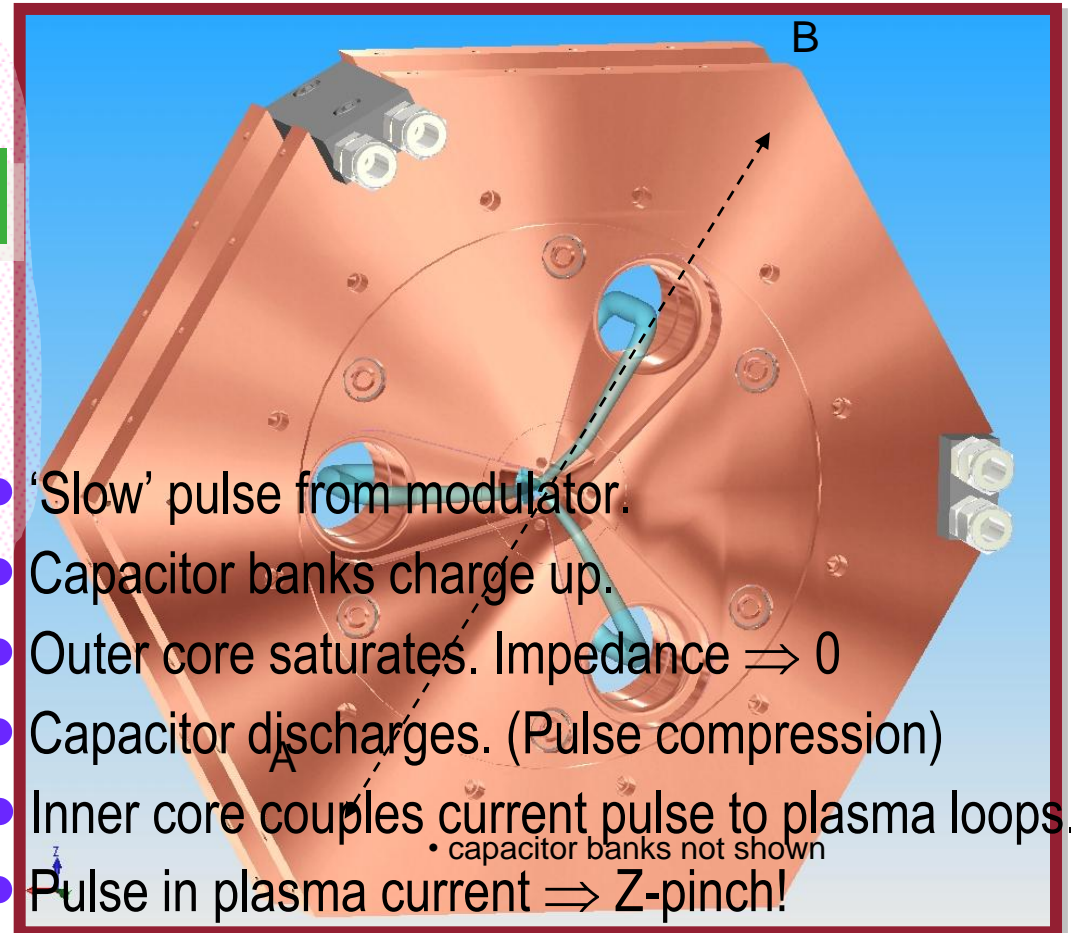
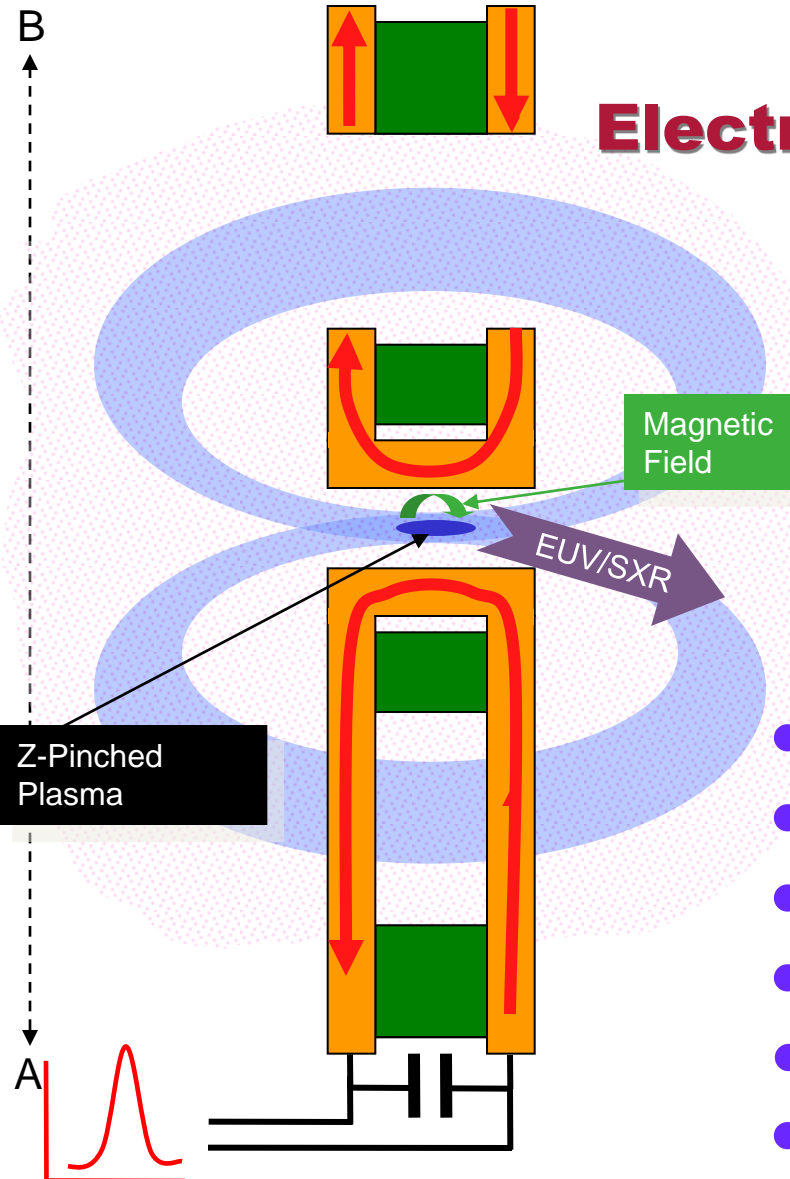
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*Stephen F. Horne, Matthew M. Besen,  
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Paul A. Blackborow, Deborah S. Gustafson*

# Agenda

- Background on the EQ-10 Electrodeless Z-Pinch™ EUV source
- New Metrology
- Improvements of source to increase power and brightness
- Modeling of Laser Enhanced EUV Source
- Summary

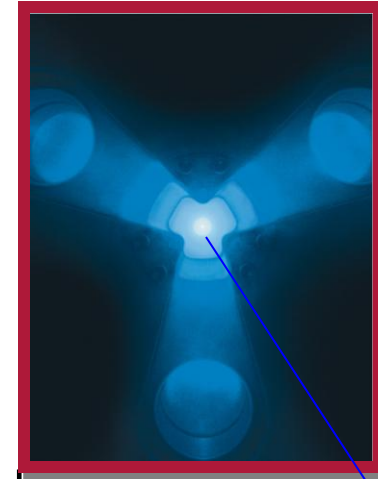
## Electrodeless Z-Pinch™ EUV Source



- 'Slow' pulse from modulator.
- Capacitor banks charge up.
- Outer core saturates. Impedance  $\Rightarrow 0$
- Capacitor discharges. (Pulse compression)
- Inner core couples current pulse to plasma loops.
- Pulse in plasma current  $\Rightarrow$  Z-pinch!

# System Reliability

- Introduced in 2005
- Shipped over 18 sources in the field
- Installations in Japan, Europe and US
- Systems being operated 24/7 with minimal downtime
- Systems integrated into tools for research and development
  - Actinic Inspection
  - Resist Outgassing
  - Mask Contamination
  - Optics Testing

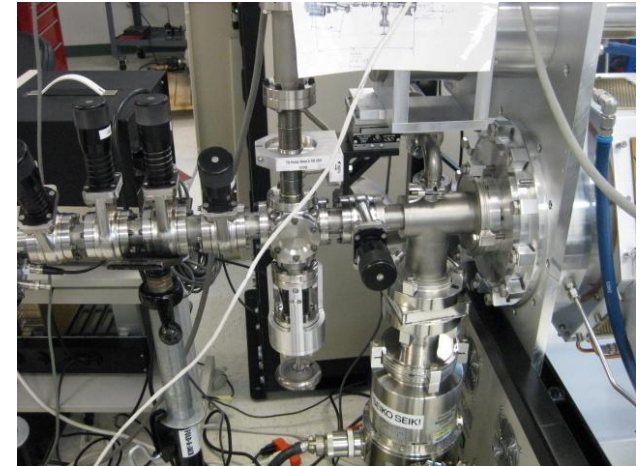
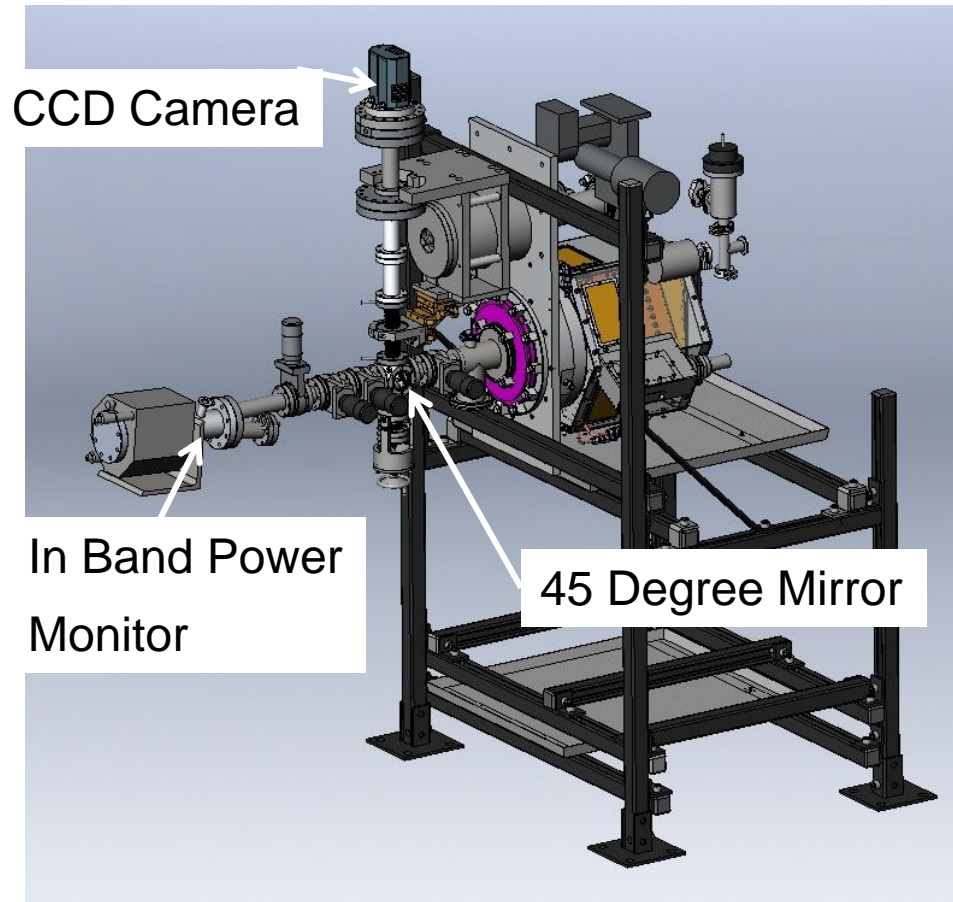




## **Recent Improvements in EQ-10 Brightness and Power**

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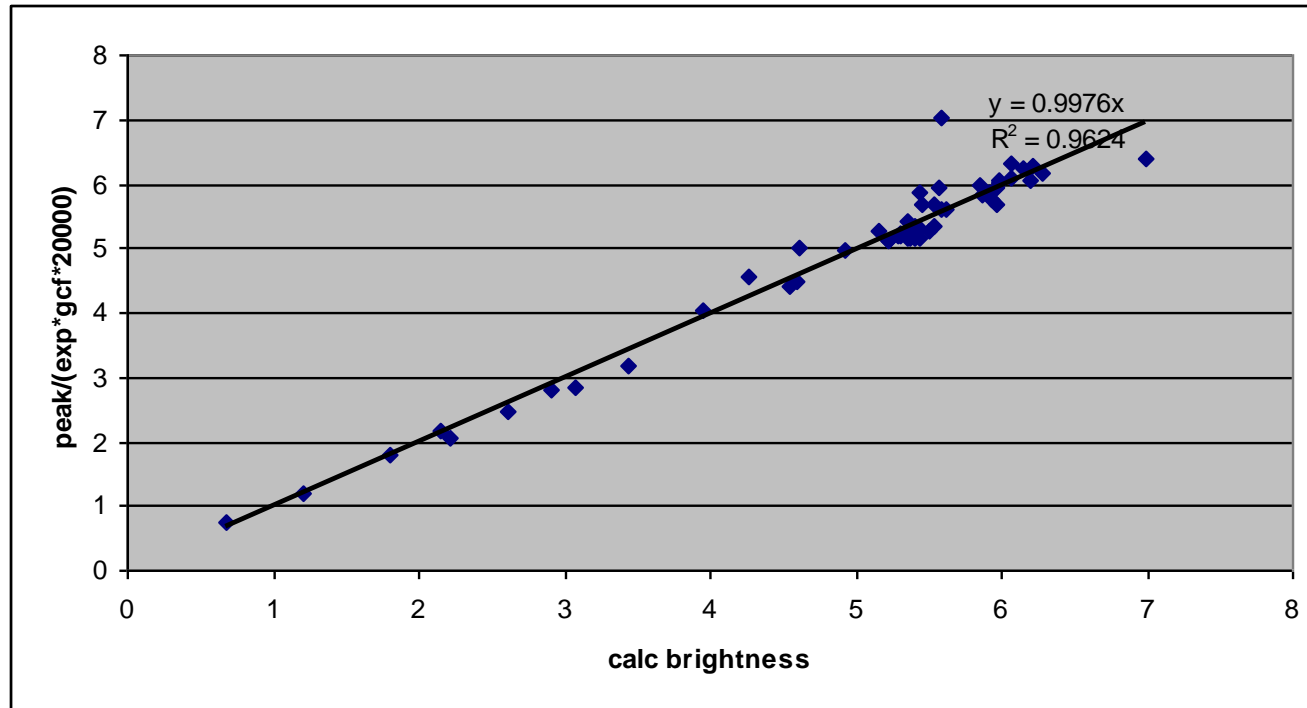
# New Dual Diagnostic Brightness Measurements



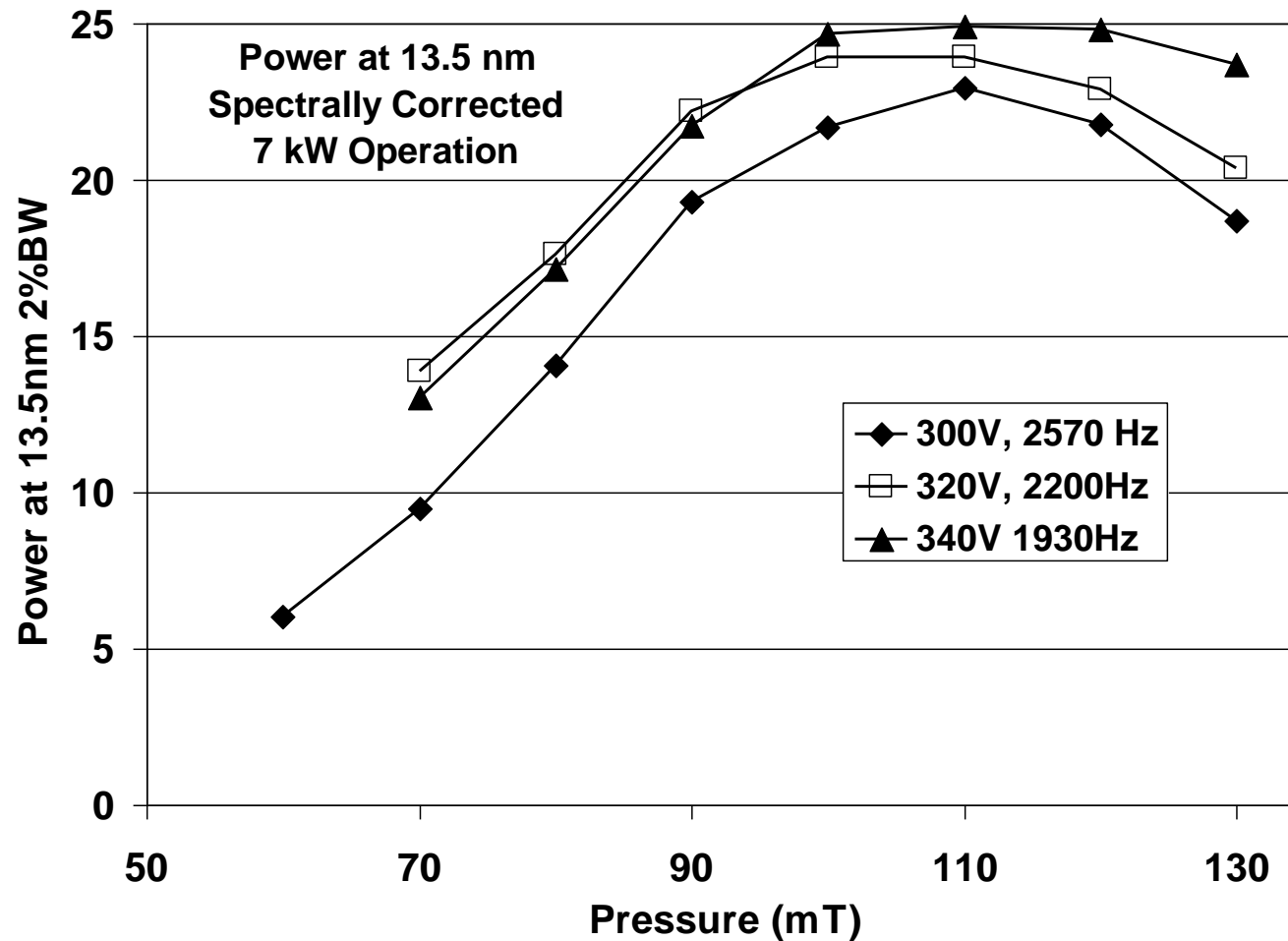
- EUV Power Monitor is calibrated at NIST

# Better Correlation for Brightness

- Allows brightness estimate by camera image
- Can optimize source while operating to find brightest plasma

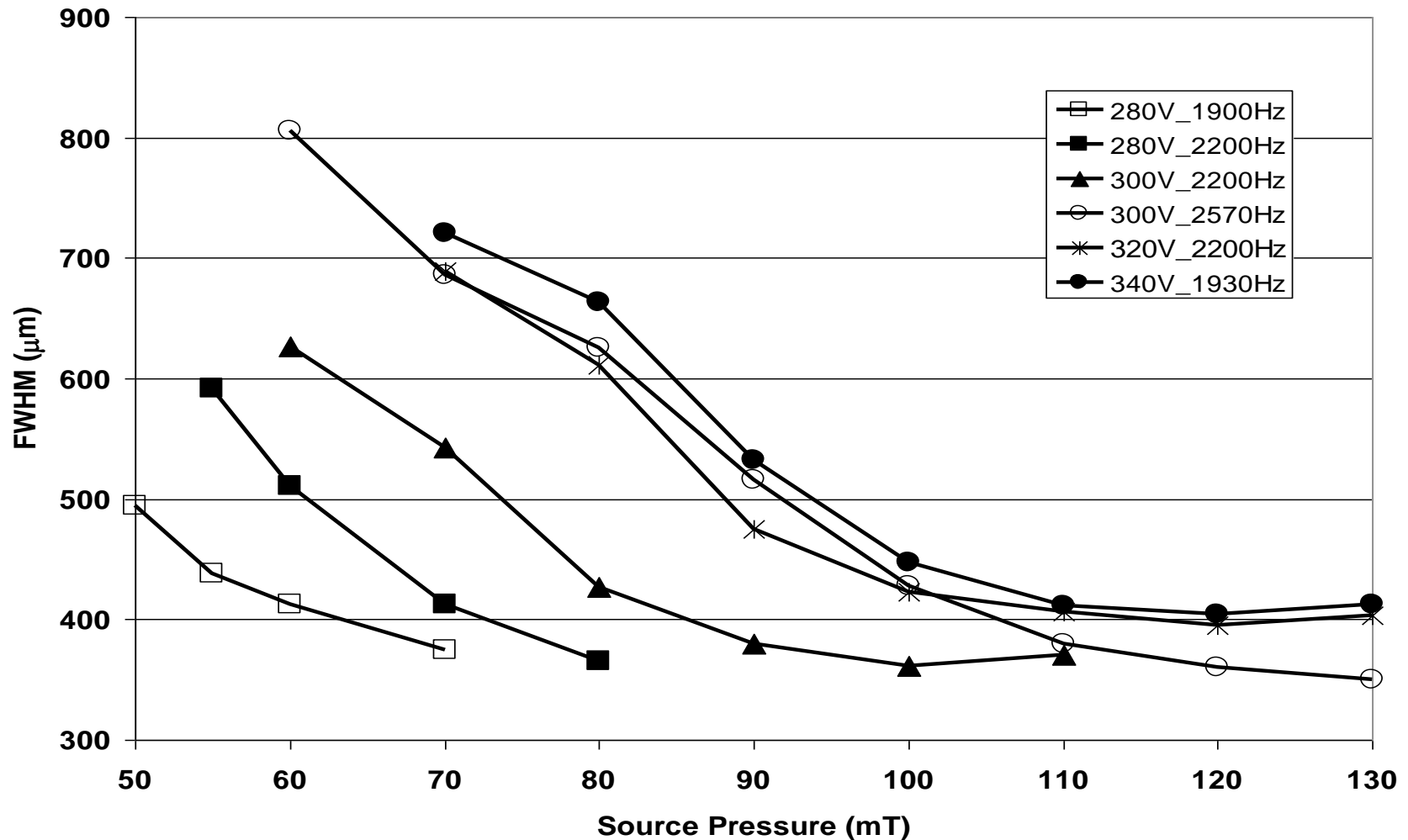


# Power ~ 25 Watts into $2\pi$

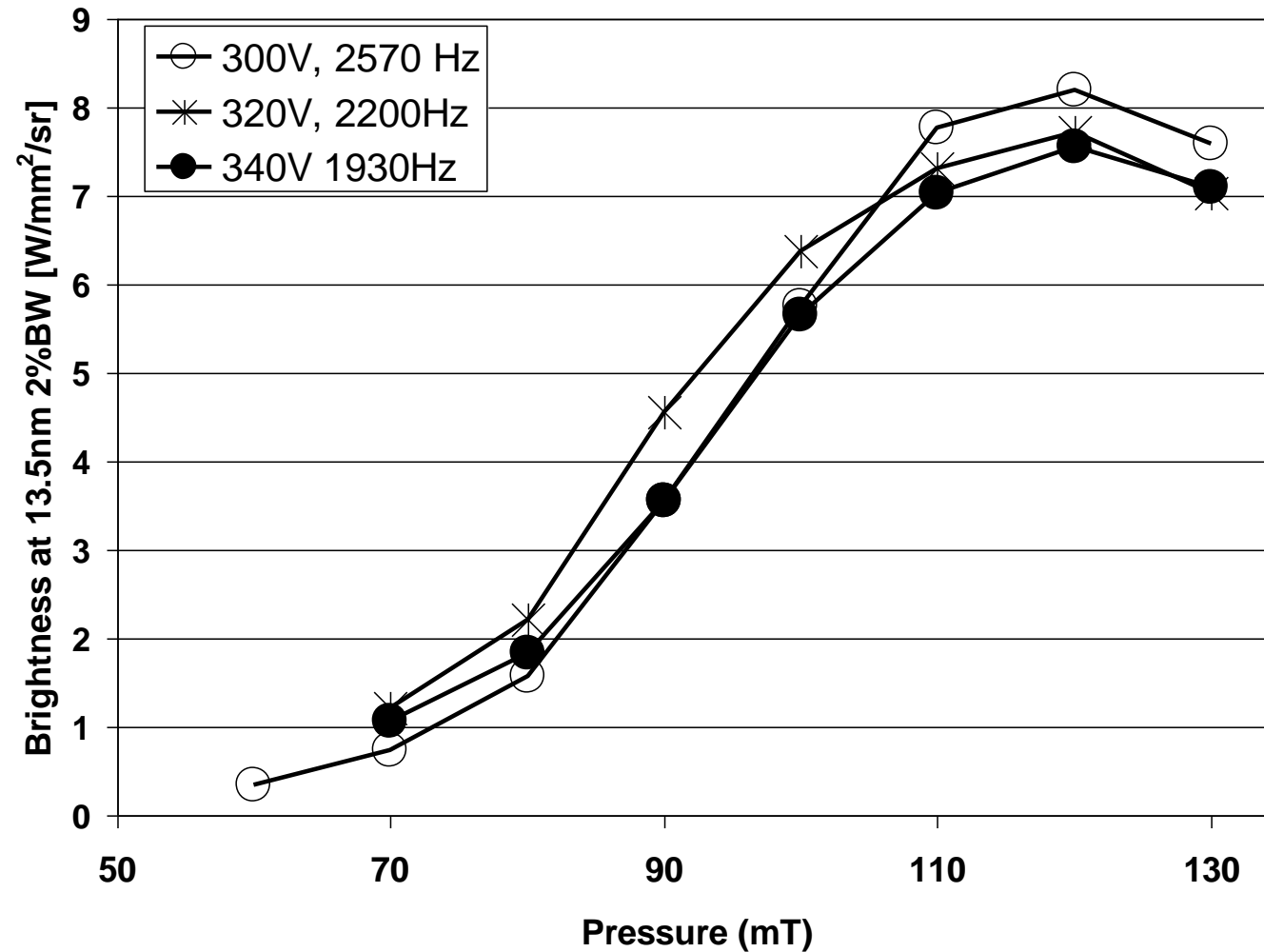




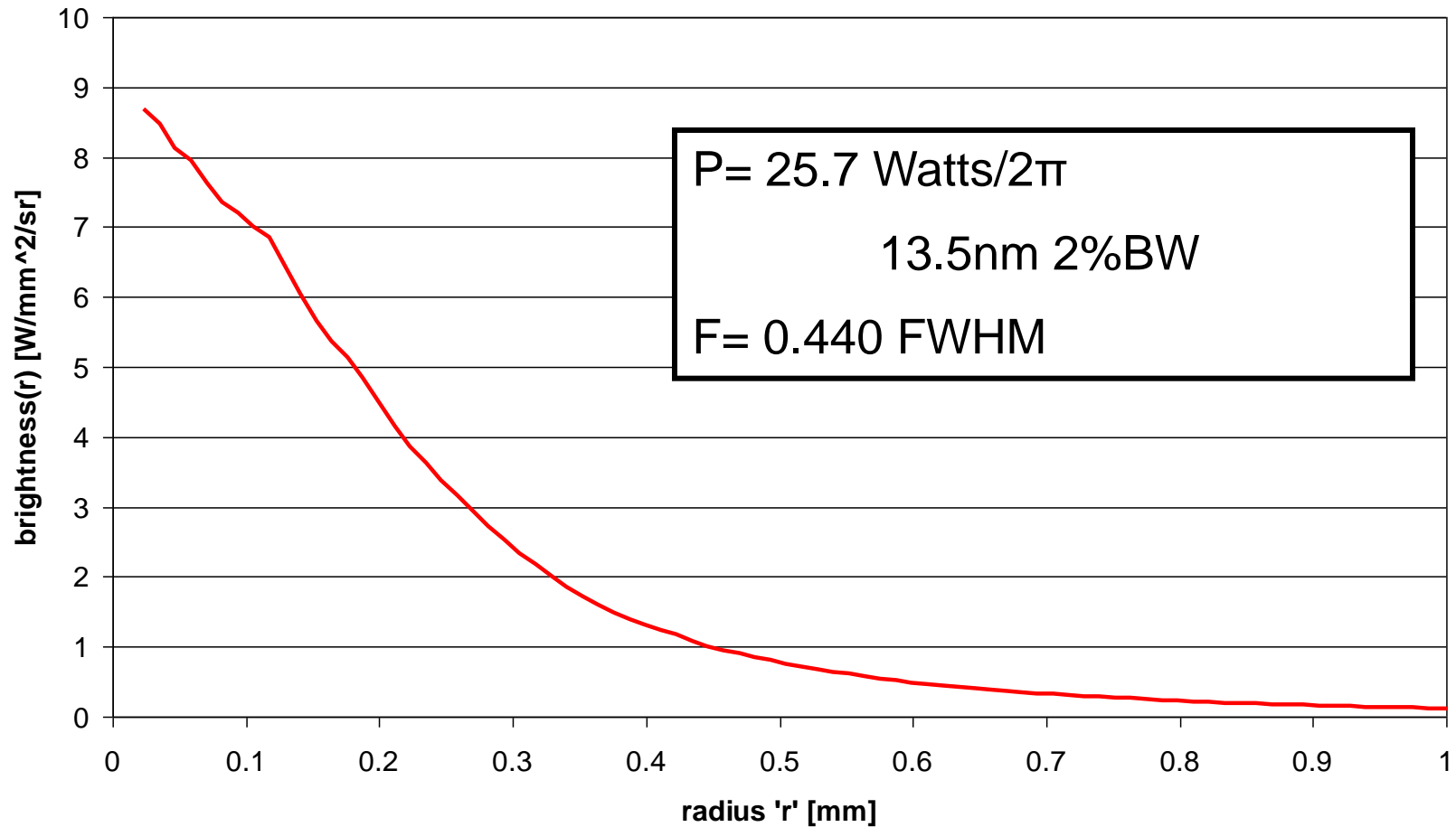
# Size Controllable via Pressure



# Brightness Optimizes at Higher Pressure



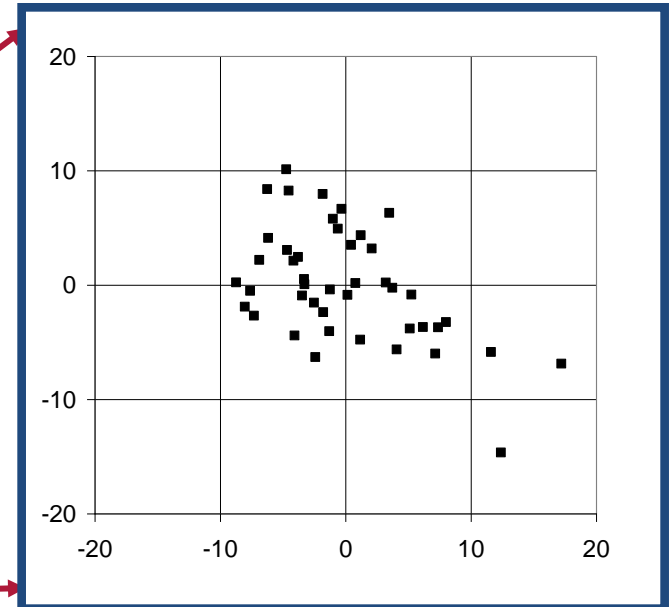
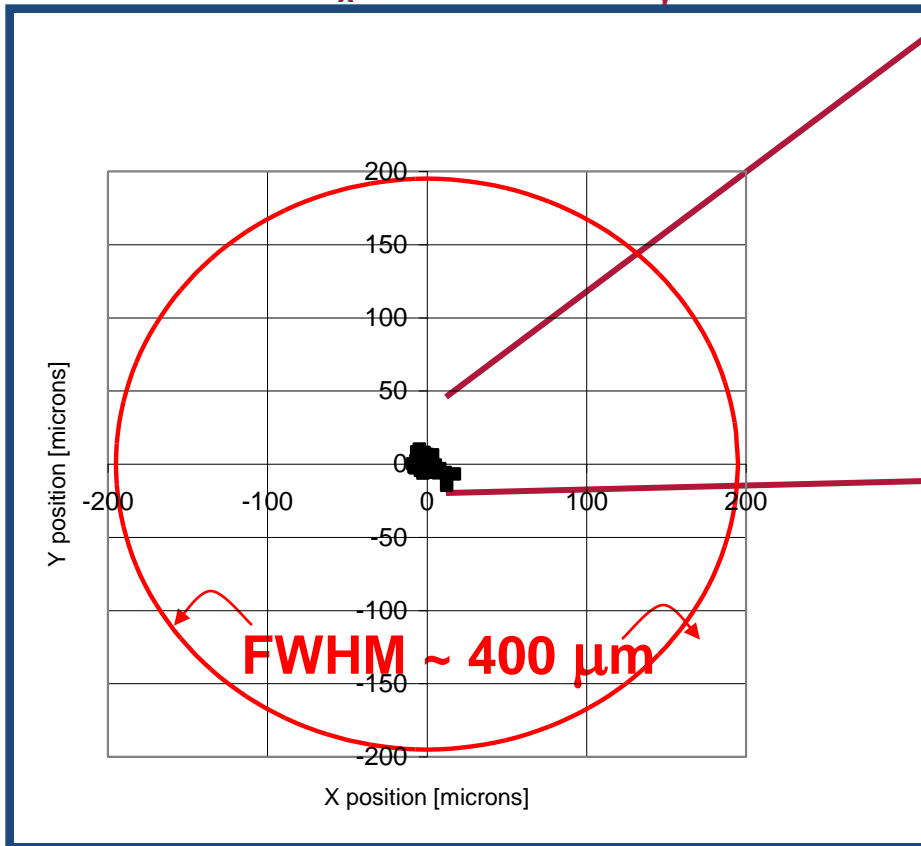
# Optimize for Peak Brightness



# Stability in EUV Plasma Position **ENERGETIQ**

- Image recorded once an hour for over 300 million pulses (~44hours) of continuous operation. Position then extracted from images:

– Position:  $\sigma_x = 5.8 \mu\text{m}$  and  $\sigma_y = 5.0 \mu\text{m}$



- Brightness remains constant
- This is open-loop stability:  
No feedback!

## Current performance...

- Based on standard EQ-10 High Reliability Source
  - Utilizes new better cooling bore design
  - Improved modulator
- Design allows for up to 7kW input power
  - Improved cooling of source and modulator
- Specifications
  - >20 W @ 13.5nm  $\pm 1\%$  Power in  $2\pi$
  - **$\sim 8 \text{ W/mm}^2\text{-sr}$  brightness**
  - 24/7 Operation



# Actinic Mask Inspection and Metrology Requirements

- Actinic Blank Inspection, AIMS and Patterned Mask Inspection are critical to the success of EUV lithography
- Major OEMs have programs for development of these tools
- There is no commercial source on the market to meet the “production” needs for these tools
- Brightness  $\sim 50\text{-}100 \text{ W/mm}^2\text{-sr}$  is desired for production tools



# **Laser Enhanced Electrodeless Z-Pinch EUV Source Concept**

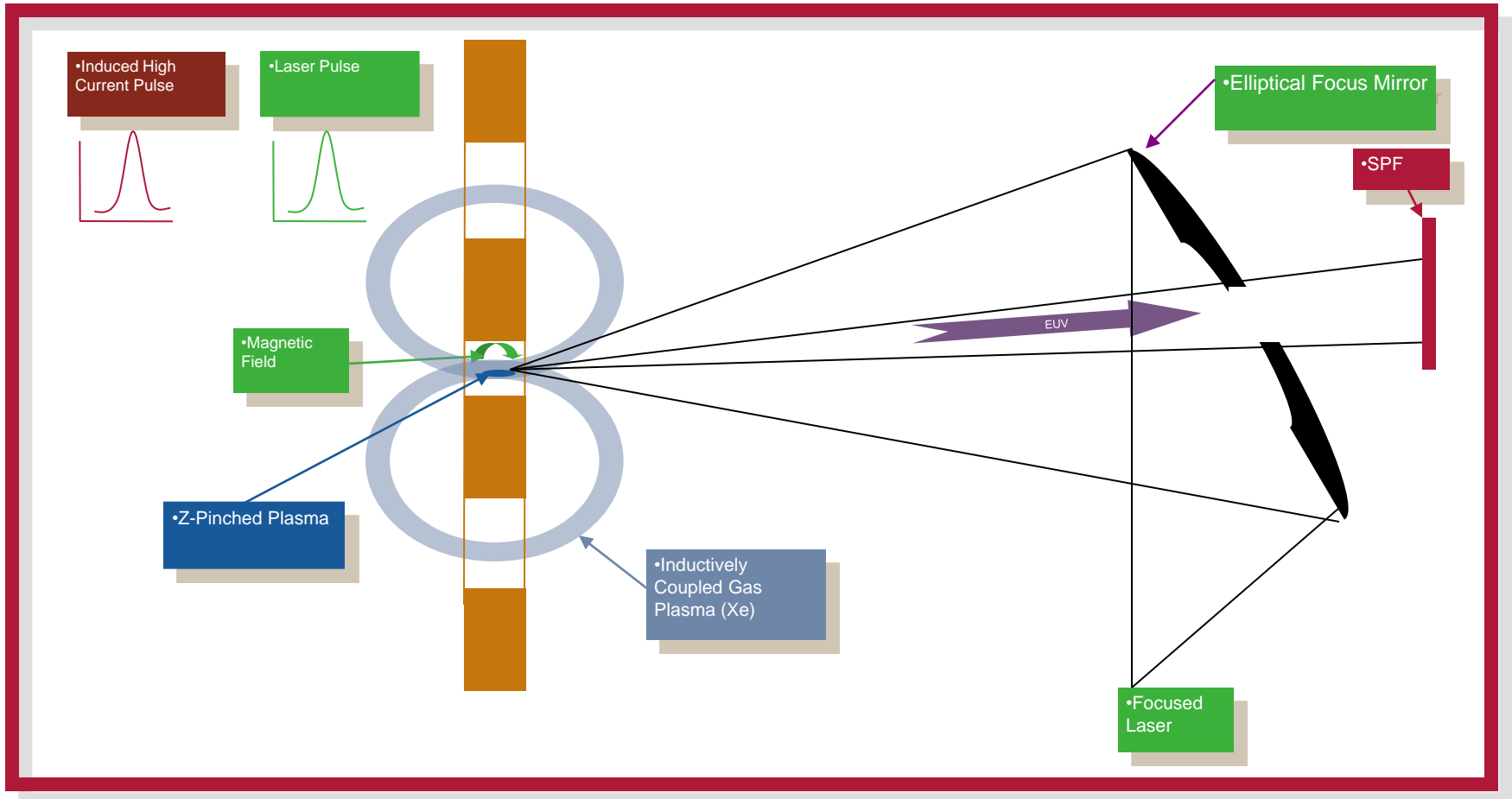
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## Use Z-pinch as Pulsed Laser Target.

- Goal -- increase source brightness while retaining key performance features of the EQ-10
- Brightness of  $\sim 100\text{W}/\text{mm}^2\text{-sr}$ 
  - Plasma size  $\sim 50\mu\text{m}$
  - $\sim 1\text{-}2\text{ W}/2\pi$
  - Continued excellent plasma and pulse-to-pulse stability (inherited from demonstrated stability of plasma target)
- Standard LPP starts from a cold Xe or Sn target --
  - Laser must ablate the cold target, then ionize it, and finally heat the resulting plasma to the 20-30 eV range.
  - Pre-heating pulse increases efficiency
- Z-pinch target is already a plasma; can be optimized for peak performance



# Laser Enhanced Electrodeless Z-Pinch EUV Source

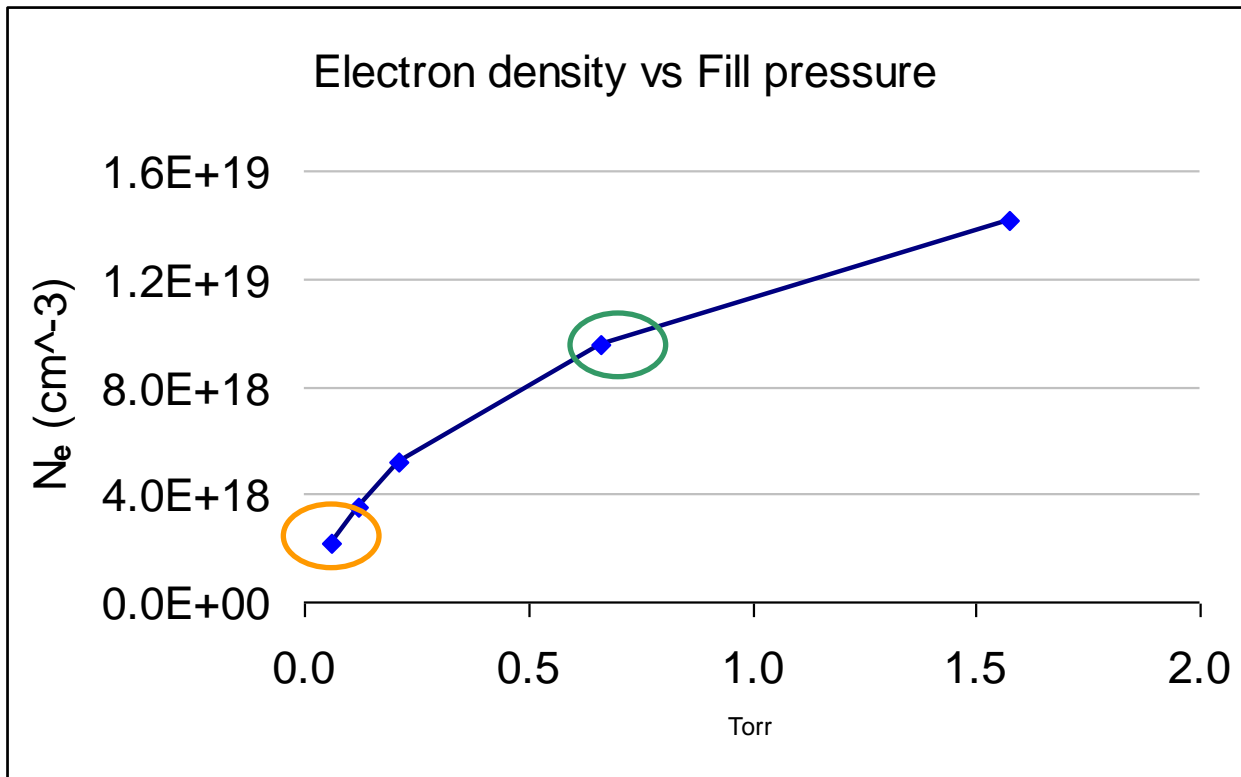


# How to Estimate Performance and Requirements?

- Scale to existing data
  - Our data for target development.
  - Published data
- Use code results (with care) to address specific issues.
  - Coupling of laser to target plasma
    - ❖ Average charge state vs  $N_i$ ,  $N_e$ ,  $T_e$
    - ❖ Optical depth at laser wavelength
  - EUV output
- Primary code used: FLYCHK (NIST)
  - Y. Ralchenko, "Online databases and computational tools for non-LTE spectroscopy," *Physica Scripta*, vol. T134, pp. 014 025+, 2009. [Online]. Available: <http://dx.doi.org/10.1088/0031-8949/2009/T134/014025>

## First, make a dense target...

Assume pinch compression and compressed plasma energy density are similar to our usual plasma; similar Bennet current. Use FLYCHK to relate  $N_i$ ,  $N_e$ ,  $T_e$ ,  $Z$



Energy density scales as  $T_e * (Z+1) * N_i$ ;

$N_i$  scales as fill pressure.

Benchmark to our experimental results

$T_e = 25$  eV,  $Z = 10$ ,  
Pressure = ~0.06 Torr,  
Compressed  $N_e = \sim 2.0 \times 10^{18}$

$T_e \sim 5$  eV,  $Z = 4$ ,  
Pressure = ~0.66 Torr,  
 $N_e = \sim 1.0 \times 10^{19}$

# Dense enough so the laser will couple and reheat the plasma

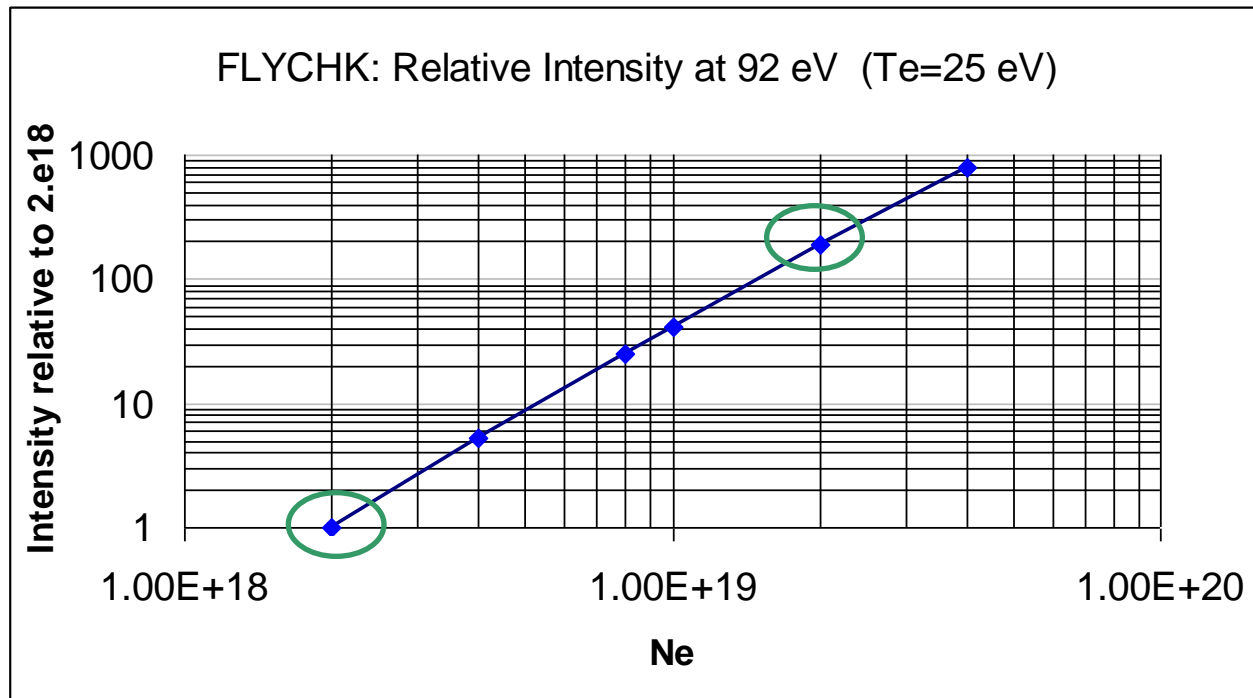
- $N_e$ ,  $T_e$  given; FLYCHK calculates charge state and radiation parameters; estimates optical depth (number of e-foldings/cm) for laser at 1064 nm.
- Experimental knob is fill pressure  $\rightarrow N_i$ ; fiddling required to match things up –
- Luckily charge state depends only weakly on  $N_e$ ...

$T_e$	Z	$N_e$	Optical depth	1/e, mm
5	3.7	1.00E+19	1.67E+01	6.00E-01
10	6.5	2.00E+19	1.85E+01	5.41E-01
25	10.3	4.00E+19	3.24E+01	3.09E-01

- As laser pulse starts, cold plasma (5 eV,  $1 \cdot 10^{19}/\text{cm}^3$ ) has short e-folding distance – good coupling.
- As plasma heats, absorption remains good.

# Estimate output --

- Bound-Bound radiation  $\sim (N_e \cdot N_i) \cdot$  (other stuff that should be roughly constant)
  - $\rightarrow$  (ratio of fill pressures)<sup>2</sup>, after reheating
  - Usual fill pressure 60-90 mT; increase by factor of  $\sim 10$
  - Expect  $\sim$  factor of 100 more intensity; FLYCHK says  $\sim 200$



- FLYCHK calculates intensity in units of Watts/(cm<sup>2</sup>-Hz-sr);
- Here scaled to unity at  $N_e=2. \text{e}18$
- At  $N_e=2. \text{e}19$ ,  $\sim 200$

## Estimate laser requirements -

- Laser should provide  $\sim 100\times$  brightness increase on per-pulse basis. Need factor of 10 over current pinch performance, so reduce pulse rate from 2000 to 200 Hz.
- Need  $\sim 1\text{W}$  output in EUV. Typical CE in Xenon  $\sim 0.5\%$ . Implies 200 W laser.
  - CE may be higher, since plasma is already ionized...
- 200 w, 200 Hz  $\rightarrow 1\text{ J/pulse}$ .
- May prefer to optimize at higher rate, lower energy...
- Need Proof of Principle experiment at low pulse rate ( $\sim 10\text{ Hz}$ ) to validate concept.

# Results in the literature –

## Soft X-Ray Emission from a CO<sub>2</sub> Laser-Heated Z-Pinch Plasma

J. E. Tucker<sup>1</sup> and R. M. Gilgenbach<sup>1</sup>

*Received August 7, 1986; revised February 25, 1987*

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*We report results of soft X-ray measurements in which a high-power ( $10^{10}$ – $10^{11}$  W/cm<sup>2</sup>) CO<sub>2</sub> laser was used to heat a near critical density ( $<10^{19}$  cm<sup>-3</sup>) helium Z-pinch plasma. Frequency-integrated X-ray data show that the unheated Z-pinch plasma is Maxwellian with a temperature of about 30 eV. During laser heating, the X-ray emissions were enhanced over the unheated emissions. Analysis of the experimental X-ray spectra indicate that the low-energy portion of the X-ray emission spectrum (up to 600 eV) is enhanced over the baseline 30 eV Maxwellian emissions. This result is consistent with an inverse bremsstrahlung-modified distribution which results when the plasma heating rate is more rapid than the collisional thermalization rate. These results suggest that it may be possible to enhance the soft X-ray yield of a plasma lithographic source with laser heating.*

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*Plasma Chemistry and Plasma Processing, Vol. 7, No. 3, 1987*

Pulsed CO<sub>2</sub> lasers not  
commonly available  
commercially

# Basic experimental data – Proof of principle?

*The Open Plasma Physics Journal*, 2009, 2, 17-23

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Open Access

## Generation of Double Pulses in the Extreme Ultraviolet Spectral Range Using a Laser Combined Pinch Plasma Source

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<sup>1</sup>*University of Applied Sciences and Arts, Von-Ossietzky-Str.99, D-37085 Göttingen, Germany*

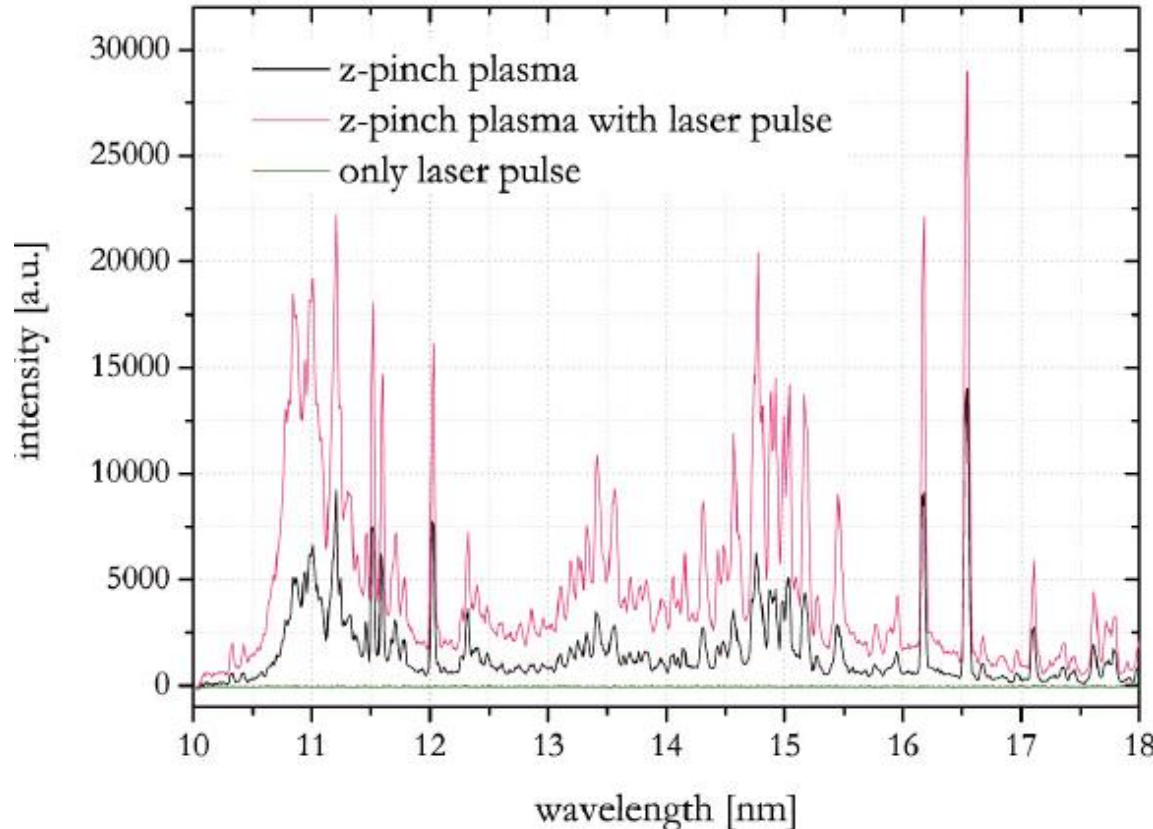
<sup>2</sup>*Laser-Laboratorium Göttingen e.V. (LLG), Hans-Adolf-Krebs-Weg 1, D-37077 Göttingen, Germany*

**Abstract:** The interaction of a dense plasma with short laser pulses (ns) is investigated. The dense plasma is created using a low-current hollow-cathode-triggered discharge. This configuration generates a dense plasma with an electron density of  $n_e \approx 10^{17} \text{ cm}^{-3}$ . Spectra are taken in the extreme ultraviolet (EUV) spectral range from 11-18 nm to estimate the temperature. The interaction between plasma and laser beam as a longitudinally pumped light source is discussed. The required properties of the plasma, according to the radial profiles of the temperature and the density, are exemplified. It is shown, that the generation of double pulses in the extreme ultraviolet spectral range is possible by reheating the residuals of an expanding dense plasma with a short laser pulse.

**Keywords:** Laser heating, inverse bremsstrahlung, plasma heating, z-pinch, hollow cathode.



S. Bruckner, S. Wieneke, and W. Viol, "Generation of double pulses in the extreme ultraviolet spectral range using a laser combined pinch plasma source." *The Open Plasma Physics Journal*. vol. 2. pp. 17-23. 2009.



Note – emitting plasma size with laser pulse is likely much smaller than the pinch size, implying much increased brightness. Laser approximately doubles EUV output.

•**Fig. (3).** Experimentally determined EUV spectra of a xenon z-pinch plasma (black) and a combined laser pulse reheated zpinch plasma (red). In comparison the sole laser pulse does not create any EUV radiation, because the charge carrier density is too low for the ignition of a plasma discharge (green).

## Closing Remarks

- The Energetiq EQ-10 EUV source is a reliable and stable source of EUV photons.
- Energetiq Sources are being used for infrastructure development globally.
- Redesign of the source offers higher power and higher brightness operation
  - Brightness of  $\sim 8\text{W/mm}^2\text{-sr}$
  - 20W/  $2\pi$ , 24/7 operation
  - Continued excellent plasma and pulse-to-pulse stability
- Introducing a laser enhancement to the stable z-pinch will increase source brightness while retaining key performance features of the EQ-10
  - Brightness of  $\sim 100\text{W/mm}^2\text{-sr}$
  - 1W/  $2\pi$
  - Continued excellent plasma and pulse-to-pulse stability
- 1:20 PM Session 9: Soft X-Ray Sources for Non-Semiconductor Applications -- laboratory-scale water window microscope



# Thank You

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